GROUND VEHICLE SAFETY OPTIMIZATION CONSIDERING BLASTWORTHINESS AND THE RISKS OF HIGH WEIGHT AND FUEL CONSUMPTION

Steven Hoffenson
Michael Kokkolaras, PhD
Panos Papalambros, PhD
Mechanical Engineering
University of Michigan
Ann Arbor, MI

Sudhakar Arepally
U.S. Army Tank Automotive
Research Development and
Engineering Center (TARDEC)
Warren, MI

ABSTRACT

Occupant safety is a top priority of military vehicle designers. Recent trends have shifted safety emphasis from the threats of ballistics and missiles toward those of underbody explosives. For example, the MRAP vehicle is increasingly replacing the HMMWV, but it is much heavier and consumes twice as much fuel as its predecessor. Recent reports have shown that fuel consumption directly impacts personnel safety; a significant percentage of fuel convoys that supply current field operations experience casualties en route. While heavier vehicles tend to fare better for safety in blast situations, they contribute to casualties elsewhere by requiring more fuel convoys. This study develops an optimization framework that uses physics-based simulations of vehicle blast events and empirical fuel consumption data to calculate and minimize combined total expected injuries from blast events and fuel convoys. Results are presented by means of two parametric studies, and the utility of the framework is discussed in a dynamic context and for evaluating casualty-reduction strategies.

INTRODUCTION

Occupant safety is a top priority of military vehicle designers, and in recent years this focus has shifted heavily toward the threat of underbody explosions due to landmines and improvised explosive devices (IEDs). IED blast occurrences and damages have increased exponentially in the past decade [1], leading to the replacement of relatively compact multipurpose vehicles, such as the High Mobility Multipurpose Wheeled Vehicle (HMMWV), with larger, more blast-protective ones such as the Mine Resistant Ambush Protected Vehicle (MRAP). Much of the improved blastworthiness of the MRAP is tied to its mass, which is approximately four times that of its predecessor [2], with a consequent decrease in mobility and fuel economy. Fuel consumption has long been targeted for improvement by environmental and national security initiatives, but both commercial and military vehicle manufacturers have often considered it a tradeoff with safety. However, recent reports indicate that convoys transporting fuel to military operations have become a major target of adversaries [3]. Thus, using vehicles that consume more fuel might be disadvantageous to broader safety objectives.

Vehicle blast protection is a subject of increasing interest, and many studies have been done by academic and government institutions with aims to improve occupant survivability under explosive threats. Due to the high costs of physically testing the responses of vehicles and occupants to underbody explosions, computational models have been developed to measure such outcomes, which are typically validated using physical experimentation [4]. Central to the validity of physical and computational tests is the biofidelity of the human dummy models, commonly referred to as anthropomorphic test devices (ATDs), and much research has gone into understanding how injuries occur to the human body in blast events. The North Atlantic Treaty Organization (NATO) published a report that compiled the results of several studies on how forces and accelerations in different body parts correspond with the likelihood of injury [5]. Since then, researchers such as Champion et al. (2009) and Gondusky and Reiter (2005) have used empirical data to better understand the frequencies of different injury types, but new public standards have not yet been established [6,7].

Emphasis on blast protection has spurred several innovations. For example, the Self-Protection Adaptive

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
09 AUG 2011	**N/A**	**-**

4. TITLE AND SUBTITLE
Ground Vehicle Safety Optimization Considering Blastworthiness and the Risks of High Weight and Fuel Consumption

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Steven Hoffenson; Michael Kikkolaras; Panos Papalambros; Sudhakar Arepally

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA Mechanical Engineering University of Michigan, Ann Arbor, MI, USA

8. PERFORMING ORGANIZATION REPORT NUMBER
21999

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA

10. SPONSOR/MONITOR’S ACRONYM(S)
TACOM/TARDEC/RDECOM

11. SPONSOR/MONITOR’S REPORT NUMBER(S)
21999

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at the 2011 NDIA Vehicles Systems Engineering and Technology Symposium 9-11 August 2011, Dearborn, Michigan, USA, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**8**	

Roller Kit (SPARK) was deployed as an attachment to the front end of HMMWVs and other vehicles [8]. This device detonates pressure-sensitive IEDs before the vehicle is above the explosive, thereby reducing the probability that the vehicle or occupants will be harmed in a blast event. This apparatus, however, only addresses explosive threats that are triggered by pressure and does not address remote detonation. Other innovations include the development of materials that are better suited to protect against blast threats. Ma et al. (2010) developed a nanocomposite material that has shown to be effective against ballistic and blast threats, and Lockheed Martin has developed a Macro-Composite Protection System with better protection and lighter weight [9,10]. Such materials can be implemented in new vehicles to improve safety, but adding mass continues to enhance blastworthiness regardless of the material.

Military vehicle designers focus on two general areas for occupant safety: the vehicle structure itself, and the occupant compartment and seating system. Structural design has seen improvements with v-shaped hulls to deflect blast energy and stronger materials, and occupant compartment design has made similar strides with energy-absorbing seat systems and impact absorbing floor pads such as Skydex [11]. Kargus et al. (2008) developed a test methodology and conducted physical experiments with vertical and horizontal shock machines to evaluate the impact of three different seating systems on ATD loading [12]. Arepally et al. (2008) used data from vertical drop tower experimentation to develop and validate a mathematical model for occupant response to blast loading, and a parametric study was conducted with a range of blast pulses and different seating design configurations [13].

Several arguments have been made over the years for improved fuel economy in U.S. military vehicles: the environmental impact of carbon emissions, national security concerns regarding dependence on supplies from geopolitically unstable regions, and costs. Safety advocates tend to claim that occupant safety is more important than fuel-related concerns. This study seeks to show that fuel consumption has a more complex relationship with overall personnel safety. The next section presents the development of a combined model to account for safety concerns related to both blastworthiness and fuel consumption, where unknown parameters are outlined and estimated. Subsequent sections present the results of optimizing this model under different scenarios and assumptions, along with discussions of the implications of these results and possible directions for further research.

MODEL DEVELOPMENT

A mathematical modeling framework was developed to quantify the impact of vehicle and seating design variables on blast protection and fuel consumption, as well as the impact of fuel consumption on fuel convoy casualties. Here, a casualty refers to any personnel injury of at least moderate severity as defined by the Abbreviated Injury Scale (AIS) [14], including fatalities. The ensuing subsections present the blastworthiness modeling technique, which takes advantage of physics-based computational models of the vehicle and a vertical drop tower system, the fuel consumption model, which uses empirical data on military vehicles, and the joint systems optimization formulation that seeks to minimize total casualties by finding an optimal vehicle mass.

Blast Protection Modeling

Using a simplified rigid finite-element vehicle model (shown on the left of figure 1) combined with a multibody dynamics-based vertical drop tower model (shown on the right in figure 1) developed and validated by Arepally et al. (2008), computational designs of experiments were conducted to determine the impact of vehicle mass, blast parameters and seating system design variables on occupant injury probability. The link between the two models is the blast pulse, or acceleration versus time profile located at the driver's seat, which is an output of the vehicle model and an input to the drop tower model. Observing that the blast parameters and vehicle mass had little impact on the shape and duration of the computed blast pulse, this curve was parameterized by the highest, or peak, acceleration (a_{peak}) value, measured in G's.

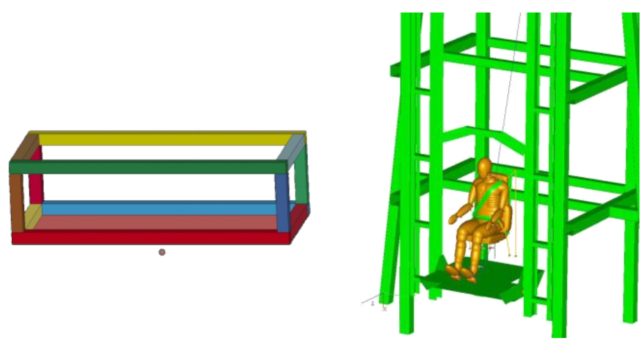

Figure 1: *Left*: finite-element vehicle-representing blast model, *right*: multibody dynamics-based occupant and seating system vertical drop tower model

The vehicle-blast simulation was conducted with 100 variations using Latin hypercube sampling over a range of values for vehicle mass (m_v), explosive charge mass (m_c), and charge location in the longitudinal (x_c) and lateral directions (y_c), and a polynomial surrogate model was fit to the results using linear regression with a coefficient of determination (R^2) of 0.96 [15]. Due to the unpredictable nature of IEDs, charge parameters are not prescribed, but rather treated as random variables with some postulated

multivariate distribution; the charge mass was assumed to be normal and the location uniformly distributed beneath the vehicle. The surrogate model was then used for Monte Carlo simulations of these input parameters, and the result was an approximately normal distribution of peak acceleration as a function of vehicle mass. The resulting mean (μ_{apeak}) and standard deviation (σ_{apeak}) of peak acceleration as a function of vehicle mass was modeled using power regression, given by Equations (1-2).

$$\mu_{a_{peak}} = 4\times10^{6} m_v^{-1.023} \quad (1)$$

$$\sigma_{a_{peak}} = 2\times10^{6} m_v^{-1.035} \quad (2)$$

The next step was to input the blast pulse curve as a prescribed motion to the occupant drop tower model, and a 300-point Latin hypercube of samples was computed varying the peak acceleration, seat energy-absorbing (EA) system stiffness (s_{EA}), seat cushion foam stiffness (s_c), and floor pad stiffness (s_f). The output of interest is the probability of injury to the occupant, calculated using the NATO criteria for axial force in the upper neck (F_{neck}), lower lumbar spine (F_{lumbar}), and lower tibia (F_{tibia}) [5]. Each of the three force responses was fit with a polynomial surrogate model using linear regression to create closed-form equations for body forces as functions of the four inputs, with coefficients of determination of 0.95, 0.95, and 0.98, respectively. The criteria themselves were specified by NATO with thresholds that represent a ten-percent probability of sustaining a moderate injury, defined as an AIS level 2 injury [14]; however, only one of the three criteria had an associated curve that prescribed probability of injury as a function of axial force, namely, the tibia injury criterion [16]. Thus, similar injury curves were postulated as Weibull functions for the lumbar spine axial force and the upper neck axial force, and they were used in the optimization formulation presented as Equation (3).

The variability in the charge parameters is incorporated in this formulation as a variation in a_{peak} using the normal distribution formula, $\varphi(a_{peak})$, and equations (1-2) Since explosives cannot physically have a negative size, a_{peak} values are constrained to be non-negative, and thus the distribution is integrated across the range $(0,\infty)$. This distribution function multiplied with the overall probability of moderate injury (P_{injury}) provides the total injury probability given that a blast event occurred, which is the objective to be minimized.

Here, the only constraints are lower (lb) and upper bounds (ub) on the three seating system design variables: s_{EA}, s_c, and s_f. The solution to the problem in Equation (3) delivers the blastworthiness-optimal seating system design for a given vehicle mass and the probability of injury associated with that vehicle. This probability presented across a range of vehicle mass parameters in figure 2, which represents a Pareto frontier with two design objectives: minimize injury probability and minimize vehicle mass.

$$\underset{s_{EA},s_c,s_f}{\text{minimize}} \int_0^{\infty} P_{injury} \cdot \phi(a_{peak}) \cdot da_{peak} \quad (3)$$

$$\text{where} \quad P_{injury} = 1-(1-P_{neck})(1-P_{lumbar})(1-P_{tibia})$$

$$P_{neck} = 1-e^{-\left(F_{neck}/5.82\right)^{6}}$$

$$P_{lumbar} = 1-e^{-\left(F_{lumbar}/7.57\right)^{18.5}}$$

$$P_{tibia} = 1-e^{-\left((1.57+0.42F_{tibia})/5.13\right)^{7.43}}$$

$$\phi(a_{peak}) = \frac{1}{\sqrt{2\pi\sigma^2_{a_{peak}}}} \cdot e^{\frac{-(a_{peak}-\mu_{a_{peak}})^2}{2\sigma^2_{a_{peak}}}}$$

$$\text{subject to } lb \le s_{EA}, s_c, s_f \le ub$$

Fitting a curve to these data yields a closed-form expression for seating system-optimized occupant injury probability as a function of vehicle mass, shown in Equation (4), which decreases asymptotically toward zero as mass approaches infinity.

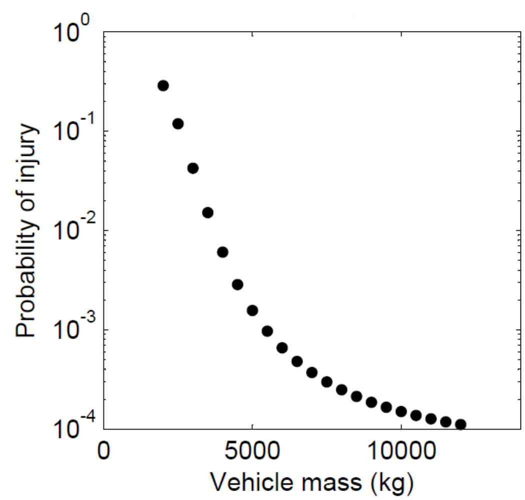

Figure 2: Optimized injury probability vs. vehicle mass

$$P_{injury} = 2.178\times10^{14} m_v^{-4.506} \quad (4)$$

This property implies that, when solely considering blast protection, increasing vehicle mass will always decrease an

occupant's probability of injury; however, it is evident, especially considering the logarithmic scale of figure 2, that the safety returns diminish significantly on a per-kilogram basis as the vehicle mass gets high. For example, increasing the mass of a 2,500-kilogram vehicle by 1,000 kilograms decreases an occupant’s predicted injury probability by 87 percent, whereas increasing a 10,000-kilogram vehicle by the same absolute amount only reduces the injury probability by 15 percent. The authors hypothesize that the safety concerns associated with fuel consumption will at some point outweigh these marginal benefits, at which point overall safety improvements will no longer be realized with mass increases. The following subsection presents a model for fuel consumption as a function of vehicle mass.

Fuel Consumption Modeling

The fuel consumption model was developed using empirical data, rather than mathematical simulation, based on publicly available specifications of presently employed U.S. ground vehicles [2]. The database included 48 U.S. Army ground vehicles with information on vehicle curb weight, driving range, and fuel tank capacity, from which estimates of fuel consumption (in gallons per mile) for each vehicle were calculated. As expected, fuel consumption tends to increase as curb weight increases. A linear fit with coefficient of determination of 0.92 is presented in Equation (5) and shown, along with the data points, in figure 3. Here, FC is fuel consumption and m_v is again vehicle mass in kilograms.

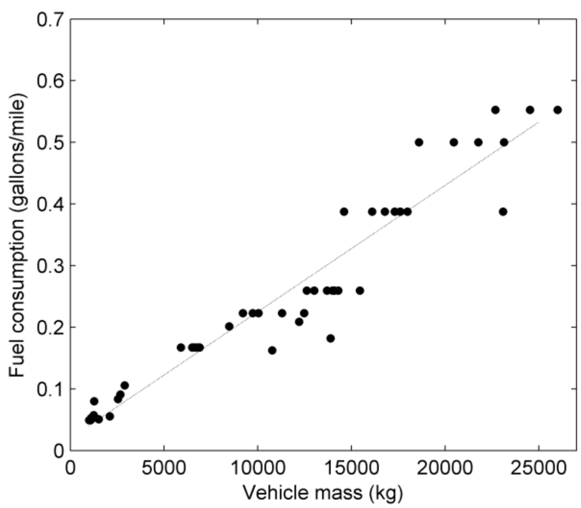

Figure 3: Fuel consumption vs. vehicle mass

$$FC = 2.0528 \times 10^{-5} m_v + 1.9705 \times 10^{-2} \qquad (5)$$

This model intentionally disregards vehicle powertrain design parameters, and in doing so operates under the assumption that these data represent vehicles with powertrain designs optimized for their respective masses. If the model were enhanced to include such powertrain factors, constraints would be needed to ensure that the vehicles meet the specification requirements of the military, such as minimum acceleration and top speed. We postulate that these performance attributes have their own contributions to the safety of ground personnel, and this is left as an opportunity for future research.

Combined Casualties Model

These two models have been combined to generate a total number of casualties that can be expected when a particular multipurpose vehicle is in operation, based entirely on its mass with the assumption that other design parameters have been optimized accordingly. This framework is based on several estimates regarding the magnitude of some of the threats facing ground troops, which are difficult to verify due to a lack of publicly-available data. Therefore, the results presented here are not suitable for detailed decision-making; rather, the modeling and optimization process can provide insights on tradeoffs when designing new military ground vehicles and making strategic contracting and deployment decisions. The novelty of the approach is the inclusion of fuel consumption into the safety design optimization formulation of a multipurpose vehicle, such as the HMMWV or the MRAP, which accounts for a significant portion of ground personnel trips.

For such modeling purposes, estimates are needed for the total number of blast and fuel convoy casualties each year. From available data and assuming that devices are planted and detonated at the same rate, it can be inferred that approximately 17,000 blast events occur in a year [17]. Additional information needed to develop the model are the percentage of these blast events that strike the particular multipurpose vehicle of interest, as well as the average number of occupants traveling in these vehicles. For this scenario, we postulate that 50 percent of all blasts strike multipurpose vehicles that typically contain four occupants each.

An estimate of total fuel convoy casualties per year in a particular theater is based on 6,000 fuel convoys deployed each year with an average of one casualty per 24 convoys [3]. Data on total fuel consumption in the same theater show that 620 million gallons of fuel is transported by convoys each year [3]. In order to use the formulation in Section 4.2 to calculate the impact of multipurpose vehicle fuel consumption on these fuel convoy requirements, it is also necessary to estimate the percentage of total military fuel consumption that is used by multipurpose ground vehicles, as well as the mass of currently employed multipurpose

vehicles. The results presented in the subsequent section are based on the assumptions that 20 percent of total fuel is used by multipurpose vehicles, and the average of these vehicles is 5,000 kilograms. This is slightly higher than the mass of a loaded and up-armored HMMWV to account for the smaller proportion of the heavier MRAP vehicles that are currently in use. The input parameters are summarized in table 1.

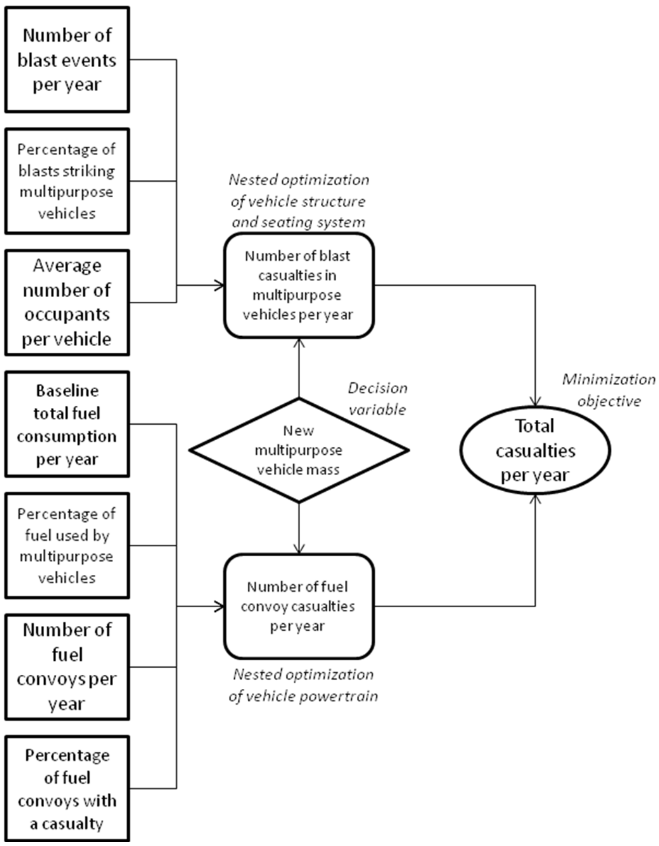

Figure 4: Combined casualty framework

The purpose of combining these models is to find the optimal multipurpose vehicle mass for minimizing expected casualties. By assembling the parameters in the manner presented in figure 4, equations (4) and (5) are used to calculate the impact of a new vehicle mass variable on the total number of casualties. In order to account for different types of injuries that are not captured by the blast model, such as hard contact with the vehicle interior, ejection from the vehicle, and intrusion of vehicle components, Equation (4) was inflated by an arbitrary factor of 2. This assumes that the axial forces in the occupant's body only account for half of the injuries that occur, and the remaining injury modes are correlated with vehicle mass in an identical manner to these forces. Since the blast protection model will drive the vehicle mass up and the fuel consumption threat model will drive vehicle mass down, a non-trivial optimal solution is anticipated. The results presented in the following section use the DIRECT derivative-free optimization algorithm to find the best value of the decision variable, the new multipurpose vehicle mass m_v, and arrive at the optimal safety outcome [18]. This algorithm was chosen because the optimization problem is unconstrained and requires minimal computational expense. Changes in two of the parameters are also explored, and their implications are discussed.

Table 1: Baseline scenario parameters

Parameter	Baseline Value
Number of blast events per year	16,800
Percentage of blasts against multipurpose vehicles	0.50
Average number of occupants per vehicle	4
Baseline multipurpose vehicle mass (kg)	5,000
Baseline total fuel consumption (gallons)	620,000,000
Percentage of fuel consumed by multipurpose vehicle	0.20
Baseline number of fuel convoys per year	6,000
Percentage of fuel convoys with a casualty	0.042

RESULTS

The results of optimizing the baseline scenario are presented in table 2. With the assumptions outlined above, it is clear that the blast threat dominates the formulation and the resulting optimal multipurpose vehicle mass is nearly double the original mass of 5,000 kilograms. Increasing the vehicle mass in this way reduces the annual number of casualties from 565 to 305, a decrease of 46 percent, and it is evident that the large majority of the resulting casualties are from fuel convoys.

Table 2: Optimization solution for baseline scenario

	Pre-optimization	Post-optimization
Vehicle mass (kg)	5,000	9,472
Total annual casualties	565	305
Total blast casualties	315	18
Total fuel casualties	250	288

To better understand the effect that the input parameters have on the resulting design and casualty rates, two parametric studies are presented, one varying a blast-related parameter and another varying a fuel convoy parameter. The former analysis parameterizes the number of blast events per year in order to study the effect of increased or decreased IED activity on the casualty-optimized vehicle design. Figure 5 presents these data, where the horizontal axis is the

scaling factor for the number of blast events per year, e.g.., for a scale factor of 2 the number of blasts per year is twice that shown in table 1. The vertical axis represents the resulting number of total annual casualties, and the size of the bubble represents the safety-optimal vehicle mass. Here, it is evident that reducing the blast events per year will decrease both the mass of the optimal multipurpose vehicle and the number of total annual casualties. Noting the scale on the horizontal axis, the relationship between the number of blast events and the total optimized casualties is logarithmic, as is the relationship between blast events and optimal vehicle mass. There is a near linear relationship between optimal vehicle mass and casualties.

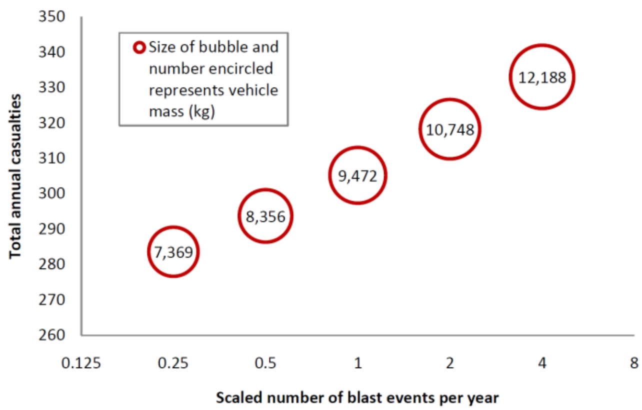

Figure 5: Parametric results varying number of blast events per year

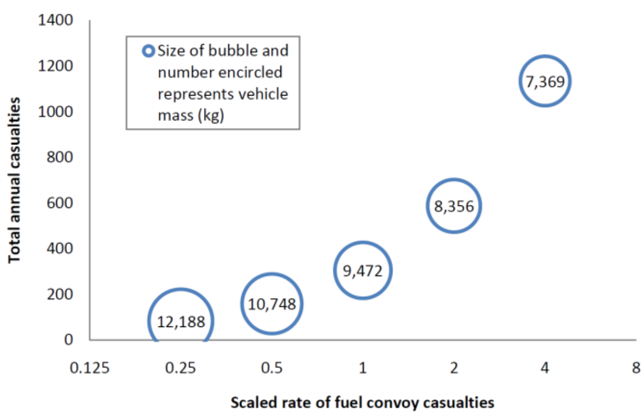

Figure 6: Parametric results varying fuel convoy casualty rate

A similar parametric study was conducted, this time choosing the fuel convoy casualty rate to vary, and the results are shown in figure 6. As expected, increasing this rate decreases the optimal vehicle mass and increases the total predicted casualties. It is interesting, and perhaps intuitive, to note that the mass values are the same as those in the blast event parametric study of figure 5; this implies that reducing a term in the blast protection model by some factor yields the same optimal vehicle design as increasing some element of the fuel convoy model by the same factor. However, the annual casualties on the vertical axis have a much higher variance when the latter rate changes, and it ranges from 83 to 1,138 as compared with the much tighter range from 284 to 333 in the blast parameter study. The relationship between fuel convoy casualty rate and total optimized casualties is nearly linear, while its relationship with optimal vehicle mass is logarithmic.

DISCUSSION

The results of the above parametric optimization studies for finding an optimal multipurpose vehicle mass when considering blast threats and fuel convoy vulnerability are generally intuitive. The blast threat drives mass up while the fuel convoy threat forces vehicle mass downward; increasing the blast threat likewise increases optimal vehicle mass, and increasing the threats to fuel convoys has the opposite effect. When either threat becomes more serious, the number of expected casualties grows, but changes to the magnitude of the fuel convoy threat tend to have a stronger impact on the total number of expected casualties with the optimized vehicle mass. While these results only present changes to two of the eight input parameters, modifying the other parameters should have similar effects. For example, changing the percentage of blast events that occur against multipurpose vehicles by some factor should have the same effect on the result as shifting the total number of blast events per year by the same factor.

Dynamic Environment Considerations

It is important to recognize that vehicle mass cannot be rapidly changed in the field, and in fact it often takes several years to make large-scale shifts in vehicle fleet composition. This is due to a number of factors including the high costs and timeline of vehicle development and manufacturing, the process of design selection and auditing, and the logistics of removing older vehicles and deploying new ones. When the threats facing vehicles are changing at a much more rapid pace, it would be impossible to keep up while using this framework to completely redesign ground vehicles. One instance in which this type of model becomes useful is when the military has a confident forecast of enemy behavior for a several-year period; it can then calculate the optimal vehicle mass and design a new vehicle or choose an available multipurpose vehicle that is close in mass.

When reliable prediction of future enemy tactics is not possible, the framework may be deployed in a dynamic context that accounts for fleet-mixing. For instance, a base may have at its disposal both HMMWVs and MRAPs, and

the strategic decision-makers must make choices on the use and mix of each vehicle class. When the threats are observed to be at a particular level, the proper parameter values can be inserted in the model and used to calculate the optimal vehicle mass. Lighter vehicles can be used for some percentage of missions and heavier ones for the remainder, such that the weighted average of the vehicles in use adds up to the predicted optimal mass. It would then be a command decision on choosing the missions to deploy each vehicle such that this optimal mixing is achieved.

Intervention Approaches

An interesting application of this combined modeling framework is to study the effect of various interventions on the expected casualties and the safety-optimal vehicle mass. Planners always seek new ways to improve operations and personnel safety, and planning interventions may affect the input parameter values or calculation models. Interventions may improve the blastworthiness of vehicles, such as using stronger materials, crushable underbody components, or impact-reducing geometries, which would necessitate an update to the calculation in equation 4. Other innovations such as the aforementioned SPARK would reduce the number of blast events on vehicles per year. This parameter could also be impacted by better detection or reduction in the number of landmines and IEDs.

Other strategies proposed would impact the fuel convoy part of the formulation, some of which are posed primarily for safety reasons and others for financial or environmental concerns [19]. Two major potential areas for intervention are the total fuel consumption per year and the percentage of fuel convoys with a casualty. Techniques to reduce fuel consumption include implementation of solar or geothermal electricity generation, electrification of the vehicle fleet, improvement of energy efficiency in base structures, and microgrids [20]. One study found that a spray-foam insulation technique could reduce building energy requirements by 80 percent, and in doing so it claimed savings of $1 billion per year and a reduction of 11,000 fuel trucks [21]. Another obvious approach is to improve efficiency of the entire vehicle fleet in operation. Other efforts can be made to directly reduce the fuel convoy casualty rate [8].

Planners can use the proposed framework to assess the broader impact of a proposed intervention on the expected casualties, objectively computing the benefit of the particular approach and comparing costs and benefits.

Opportunities for Model Enhancement

The model presented here is by no means complete. The formulation does not presently account for ballistic or missile protection capabilities. It also does not address the overlap in the data between multipurpose vehicle blast attacks and multipurpose vehicles acting as fuel convoy escorts that are attacked by explosive devices, and an additional parameter might be added to address the proportion of these events that are counted in both models. The model does not specifically account for the fuel saved from increased convoy efficiency and effectiveness, which itself would avoid the need for additional fuel convoys. Lastly, the model may be extended to include convoys that transport non-fuel items, which represent half of all convoys. Approximately 40 percent of these convoys are for water, and therefore implementing methods for obtaining and purifying local water sources could cut down on the need for water supply trucks [3].

Factors other than safety may also be considered in decision-making, such as economic or environmental impacts of fuel-related decisions. Cost can be directly correlated with fuel consumption, and an additional parameter for fuel pricing will change according to current prices and forecasts. A more complete model might deliver a quantification of the links between casualties, economic costs, and emissions, and provide insights for better planning.

CONCLUSIONS

A new modeling framework for optimizing military ground vehicle design with respect to blast protection and fuel convoy safety was developed in this paper, using a combination of physics-based modeling and empirical data. Assumptions about Army vehicle usage, fuel convoys, and blast events were made based entirely on publicly available information, and the results suggest that optimal ground vehicle mass should be somewhere between the mass of the HMMWV and that of the MRAP, depending on these initial conditions. Parametric studies were conducted to explore the impact of reducing the blast threat or the threat facing fuel convoys, and interventions were discussed that would impact several of the prescribed parameters in the model. This type of combined modeling introduces a novel capability to assist in the strategic reduction of personnel casualties.

ACKNOWLEDGEMENTS

This work has been supported partially by the Automotive Research Center (ARC), a U.S. Army Center of Excellence in Modeling and Simulation of Ground Vehicles led by the University of Michigan. Such support does not constitute an endorsement by the sponsor of the opinions expressed in this article. The authors would like to thank Dr. Matthew P. Reed of the University of Michigan Transportation Research Institute for his contributions to this study.

REFERENCES

[1] M. White, iCasualties: Operation Enduring Freedom, retrieved April 2011 from http:// icasualties.org.

[2] S.C. Connors and C.F. Foss, “Jane’s Military Vehicles and Logistics 2009-2010”, Jane’s Information Group Limited, Surrey, 2009.

[3] D.S. Eady, S.B. Siegel, R.S. Bell and S.H. Dicke, “Sustain the Mission Project: Casualty Factors for Fuel and Water Resupply Convoys”, Army Environmental Policy Institute, Arlington, 2009.

[4] R.T. Bocchieri, S.W. Kirkpatrick and B. Peterson, “Simulation-Based Design of Vehicles Exposed to Blast Threats for Improved Occupant Survivability, Safety and Security Engineering III”, WIT Press, Ashurst, Southampton, 2009.

[5] NATO Research and Technology Organisation Task Group 25, “Test Methodology for Protection of Vehicle Occupants Against Anti-Vehicular Landmine Effects”, RTO Technical Report HFM-090, Brussels, 2007.

[6] H.R. Champion, J.B. Holcomb and L.A. Young, “Injuries from Explosions: Physics, Biophysics, Pathology, and Required Research Focus”, Journal of Trauma: Injury, Infection, and Critical Care, vol 66, issue 6, pages 1468-1477, 2009.

[7] J.S. Gondusky and M.P. Reiter, “Protecting Military Convoys in Iraq: An Examination of Battle Injuries Sustained by a Mechanized Battalion during Operation Iraqi Freedom II”, Military Medicine, vol 170, issue 6, pages 546-549, 2005.

[8] K. Borjes, “The Self-Protection Adaptive Roller Kit (SPARK) – Negating the Improvised Explosive Device (IED) Threat for Soldiers and Vehicles”, Army AL&T, pages 50-53, January-March 2008.

[9] Z.-D. Ma, C. Sun, Y. Cui, Y. Liu, G.M. Hulbert, B. Raju and F. Rostam-Abadi, “Simulation and Test of Nanocomposites for Application in the Army”, Technical Report Contract Number W56HZV-09-C-0040, August 2010.

[10] C. Vanbebber, “Vehicle Armor System Has Low Density and Blast Protection”, Advanced Materials & Processes, vol 164, issue 7, page 10, July 2006.

[11] T. Deligio, “Twin-Sheet Thermoformed TPU Deployed to Iraq and Afghanistan”, Modern Plastics Worldwide, vol 87, issue 2, pages 44-45, 2010.

[12] R.G. Kargus, T.H. Li, A. Frydman and J. Nesta, “Methodology for Establishing the Mine/IED Resistance Capacity of Vehicle Seats for Crew Protection”, Proceedings of the 26th Army Science Conference, Orlando, 2008.

[13] S. Arepally, D. Gorsich, K. Hope, S. Gentner and K. Drotle, “Application of Mathematical Modeling in Potentially Survivable Blast Threats in Military Vehicles”, Proceedings of the 26th Army Science Conference, Orlando, 2008.

[14] Association for the Advancement of Automotive Medicine, “The Abbreviated Injury Scale, 1990 Revision”, Des Plaines, 1990.

[15] M.D. McKay, R.J. Beckman and W.J. Conover, “A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code”, Technometrics, vol 21, issue 2, pages 239-245, 1979.

[16] N. Yoganandan, F.A. Pintar, M. Boyton, P. Begeman, P. Prasad, S.M. Kuppa, R.M. Morgan and R.H. Eppinger, “Dynamic Axial Tolerance of the Human Foot-Ankle Complex”, Society of Automotive Engineers, Warrendale, 1996.

[17] Y.J. Dreazen, “IED Casualties Up Despite Increased Vigilance”, National Journal, 3 March 2011.

[18] D.R. Jones, “DIRECT”, Encyclopedia of Optimization, Kluwer Academic Publishers, 1999.

[19] C.F. Ward and T. Captain, “Energy Security: America's Best Defense”, Deloitte LLP, 2009.

[20] J. Whitefoot, A.R. Mechtenberg, D.L. Peters and P.Y. Papalambros, “Optimal Component Sizing and Forward-Looking Optimal Dispatch of an Electrical Microgrid for Energy Storage Planning”, Proceedings of the ASME 2011 International Design Engineering Technical Conferences, Washington, 2011.

[21] S.M. Anderson, “Save Energy, Save Our Troops”, New York Times, 12 January 2011.